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# Spectral precursors of paroxysmal phases of Stromboli

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**Abstract**
In this work we investigate the characteristics of the seismicity at Stromboli volcano during more than two years, *i.e.* from 11 May 1992 to 21 August 1994. The three paroxysmal phases of 1993 mark significant changes in the Strombolian activity; nevertheless, these are not the only ones observed. In fact, the energy content, both in terms of volcanic tremor and of number of events drops to very low values after the periods of intense activity, accompanied by a change in the spectral content of the tremor. However, equally abrupt changes in the frequency content, not accompanied by evident intensity variations, can be observed some weeks after the end of the crises. The volcano seems therefore to behave like a dynamical system with many «quite stable» states with abrupt transitions between them. An interesting observation is the appearance of an energy concentration in the spectral sectors below 3 Hz before more violent eruptive episodes; although the duration of such a phenomenon is variable, it has to be investigated as a possible precursor of potentially dangerous activity of the volcano. A continuous monitoring of the spectral content of volcanic tremor on Stromboli is confirmed to be an essential tool in order to understand the behaviour of Stromboli volcano and to try to forecast its paroxysmal phases.

**Key words** *spectral analysis – volcanic tremor – precursors*

## 1. Introduction

Stromboli explosive activity has been known for hundreds of years, with relatively small craters remaining practically unchanged through a number of strong eruptive episodes. Explosion-quakes show some typical waveforms (Peterschmitt and Tazieff, 1962; Fadeli, 1984; Beinat *et al.*, 1988; Falsaperla *et al.*, 1989), although it is quite difficult (Carniel and Iacop, 1996) to associate them to the craters (Settle and McGetchin, 1980); broadband data offer new insights (Neuberg *et al.*, 1994; Dreier *et al.*, 1994). Different craters also show characteristic dynamics of the emission of ejecta (Ripepe *et al.*, 1993). This general stability suggests independent and long conduits for the different craters (Riuscetti, 1994) and also the idea of considering Stromboli a dynamical system mainly governed by deterministic rules (Carniel, 1993). Of course a long term monitoring of the seismicity is essential in order to understand the dynamics (Schick and Müller, 1985).

As regards features of tremor, the June-October 1990 crisis, ending with a small lava flow, showed a spectral line just below 4 Hz before the eruption and a decrease in the amplitude afterwards (Riuscetti, 1994), with spectra looking as due to a source radiating waves with a «coloured Gaussian distribution» (Schick and Riuscetti, 1973). An analysis of the three paroxysmal phases of 1993 (Carniel *et al.*, 1994) confirms the observations of Riuscetti (1994). On the contrary, «no precursors of any kind could be found in the composition of the tremor» (Schick and Müller, 1985) before «normal» eruptions. This suggests that a change in the spectral content could be a forerunner of more energetic phases.

## 2. The dataset

A one-component seismic station (Beinat *et al.*, 1989) was installed by our Department near the summit of Stromboli volcano in October 1989, mainly in order to monitor the explosion-quakes; regular samplings of the persistent tremor have also been recorded since May 1990. The hardware was upgraded in May 1992 to a full three-component station (Beinat *et al.*, 1994). Periodical reports on the seismic activity based on the data recorded by this station are regularly published in the *Bulletin of the Global Volcanism Network* of the Smithsonian Institution and to such reports we refer in this paper as regards the description of volcanic activity.

In this work we investigate the characteristics of seismicity since the installation of the three-component instrumentation to 21 August 1994, in order to deal with the largest continuous and homogeneous dataset available.

The seismic station is located at 800 m a.m.s.l., approximately 300 m from the crater area (see fig. 1). The velocity sensors are three Willmore MK III tuned to a natural period of 2 s, placed on a concrete basement. The amplification factor used for the vertical component is double as high as the two horizontal components. Seismic data are transmitted analogically to a receiving site (see fig. 1) located in the village of S. Vincenzo, where the analog to digital conversion takes place at a sampling frequency of 80 Hz.

The trigger for discriminating explosion-quakes is based on the verification of two distinct conditions which are checked in consecutive 1 s windows. The first condition uses a combined amplitude-frequency threshold, while the second is based on the classical STA/LTA algorithm (Allen, 1982), *i.e.* on the ratio between the integral of the wave within the time window and the integral of a tremor sample, in order to follow tremor fluctuations. Actually, to avoid instant effects, the LTA reference value is smoothed by averaging the last tremor wave integral and the previous LTA reference value.

While the explosion-quake acquisition is controlled by the trigger algorithm, the volcanic tremor is sampled regularly; samplings are 60 s long, corresponding to 4800 points, and are recorded every 60 min.

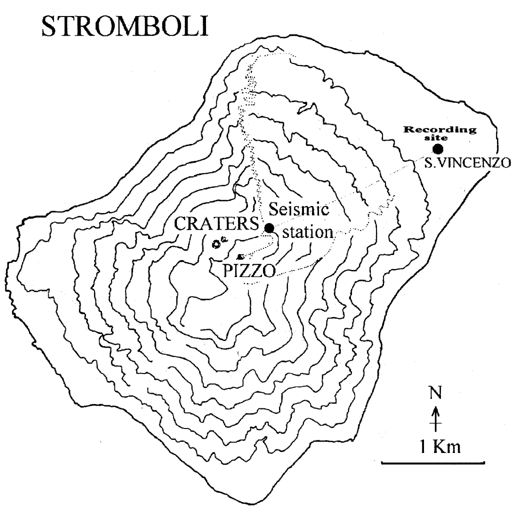


**Fig. 1.** Sketch of the island of Stromboli with the position of both the seismic station and the recording site.

## 3. The activity during the considered period

Figure 2 summarizes the seismic activity during the time interval 11 May 1992-21 August 1994. In the plot, the line indicates daily tremor intensity; the shaded bars show the number of recorded events per day, while the solid bars show the number of the stronger (saturating) explosion-quakes, characterised by theoretical ground velocity (at 1 Hz) exceeding 100 μm/s. The good efficiency of the 3 component seismic station, which has been operating almost permanently for more than two years, offers a unique opportunity to study the long term behaviour of the dynamics of the volcano.

It is worthwhile emphasizing that all the features of the recording system, *e.g.* the amplification gain and the trigger algorithm, have

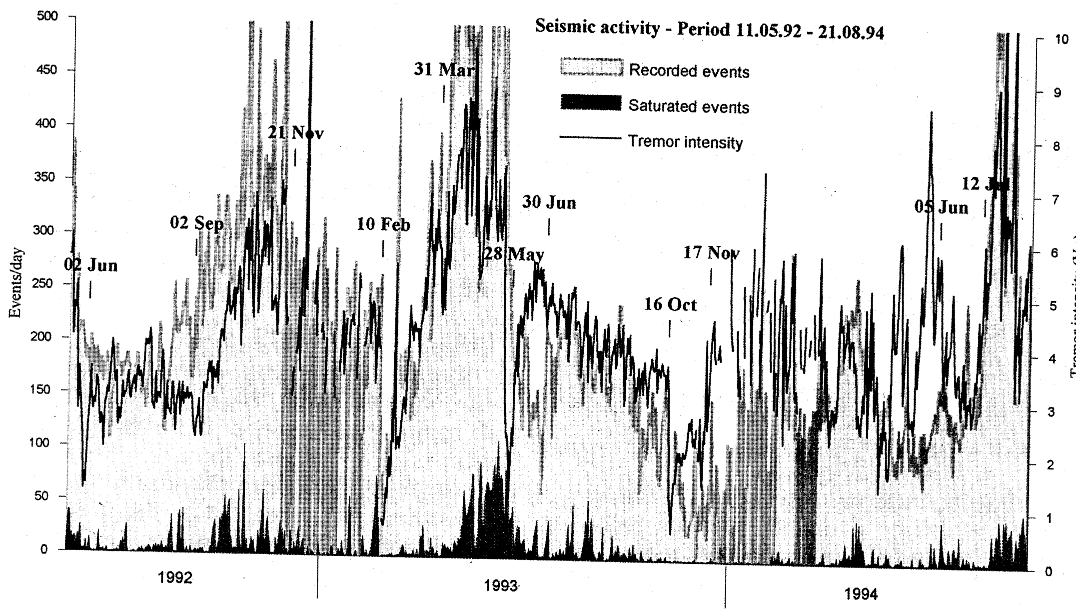


**Fig. 2.** Seismic activity during the analysed period. Shaded bars: number of recorded events per day; solid bars: events with ground velocity exceeding 100 μm/s; the line is a measure of the daily tremor intensity, obtained by integrating the absolute value of the signal over the 60 s samples and then averaging over each day. The gaps in the plot indicate periods when the seismic station was not acquiring data, mainly due to power problems during winter.

remained constant throughout the period examined here, with only one exception: from 22 July to 21 August 1994, when the station was triggering almost continuously, due to the exceptionally high level of activity. This change influences only the number of recorded events; moreover, a number greater than 500 per day (vertical scale chosen for fig. 2) already indicates almost continuous activity. The last variations in the number of events are «natural» and not related to the change in the trigger. No change was ever made to the amplification gain, so that the tremor samples, which are the main object of this study, were always recorded exactly in the same conditions.

The inspection of the plot shows that the general behaviour is characterised by three main variations during 1993, which seem to be exceptional events for the normal Strombolian activity. These variations follow the paroxysmal phases analysed in (Carniel *et al.*, 1994): two series of strong explosions (10 February and 16 October 1993) and a period of strong activity culminating in a small lava flow (16-20 May 1993).

The most evident feature of these variations is that the daily average of tremor amplitude drops to very low values. In particular, the decrease is very abrupt after the explosions of February and October 1993. It is interesting to note that the trend in the average tremor amplitude is not suitable to *forecast* possible paroxysmal phases; in fact, the February crisis happened when the tremor level was practically stable, the May lava flow followed a period of increasing tremor amplitude, while the October explosions interrupted a period in which the tremor level was characterised by a slowly decreasing trend.

Also the daily number of explosion-quakes recorded by the seismic station as well as the number of saturating events drop to quite low values after the three crises of 1993. This suggests that seismic activity, as a whole, decreases after the paroxysmal phases.

A similar but less evident behaviour can also be seen at the beginning of June 1992 and several times during 1994. From the simple time domain analysis of the seismicity it is therefore quite difficult to identify the transitions between different «states» of the dynamical system Stromboli, except for paroxysmal phases that are both very energetic and well limited in time.

## 4. Spectral analysis

In order to understand the spectral distribution of the energy during the periods before and after the paroxysmal phases with respect to «normal» periods of activity, a Fast Fourier Transform (Elliott and Rao, 1982) was carried out on all the hourly tremor samples recorded during the examined period. In total, about 14000 tremor samples were analysed with the normalization procedure described below.

The frequency interval 0.5-10.5 Hz is divided into ten 1 Hz wide sectors. The mean value $S_j$ of the spectral amplitude in each sector is computed. Additionally, the mean value $S_{tot}$ over the whole range 0.5-10.5 Hz is evaluated; this is used to normalise the sector mean value in order to determine the relative weight $S_j/S_{tot}$ of each sector with respect to the global mean value. Contour plots of the time evolution of this ratio are eventually prepared for each component after smoothing irregularities by averaging 10 consecutive hourly values in order to reduce the effect of short-lived spectral peaks and to assure stable spectral configurations.

The results are presented year by year and component by component, a good compromise between number of figures and readability of the plots.

The analysis of the activity recorded during the first months of 1992 shows the presence of several quite stable distributions separated by abrupt transitions, a feature that we will show to be peculiar for the tremor spectral evolution.

The first period examined (11 May-2 June 1992) is characterised by high seismicity, with most of the activity concentrated in only two vents, one in the NE crater, the other in the SW crater, with glowing tephra ejected to 100-150 m height (GVN, 1992a).

As regards the spectral features of tremor, most of the energy is concentrated between 1 and 6 Hz, with significant peaks emerging near 2 Hz in all the components (see figs. 3, 4 and 5), although more pronounced in the horizontal ones.

The paroxysmal phase comes to an end and the spectral distribution shows an abrupt change on 2 June 1992. The tangential and vertical components show a more pronounced concentration of energy in the lower frequency range (below 4 Hz). This behaviour is not seen in the radial component, where the most important feature is the appearance of a peak near 3 Hz; this can be seen, although less evident, also in the vertical component. The tangential component shows on the contrary a peak near 1 Hz.

The distribution of the spectral content remains quite constant until 2 September 1992; in this period also the seismicity in terms of tremor intensity and number of events shows a noteworthy stability (see fig. 2).

Another abrupt spectral transition introduces a new configuration on 2 September 1992. The shift is towards higher frequencies; most of the energy is now spread over the range from 1-2 Hz to 6 Hz. Significant peaks could be identified in the vertical component (around 3 Hz, soon disappearing, see fig. 5) and in the tangential one (around 2 Hz, constantly present throughout this phase, see fig. 4). On the contrary, no major changes can be observed in the spectrum of the radial component (see fig. 3), except for a slow shift of the 3 Hz peak towards a frequency of 2 Hz. In this period tremor intensity and number of earthquakes are constantly increasing, reaching a climax on 14-16 October. The number of saturating events is also particularly high. Most of the eruptive activity is concentrated in the NE crater, with almost continuous spatter ejection and frequent explosions. Rare strong explosions at SW crater feed black plumes about 200 m high (GVN, 1992b).

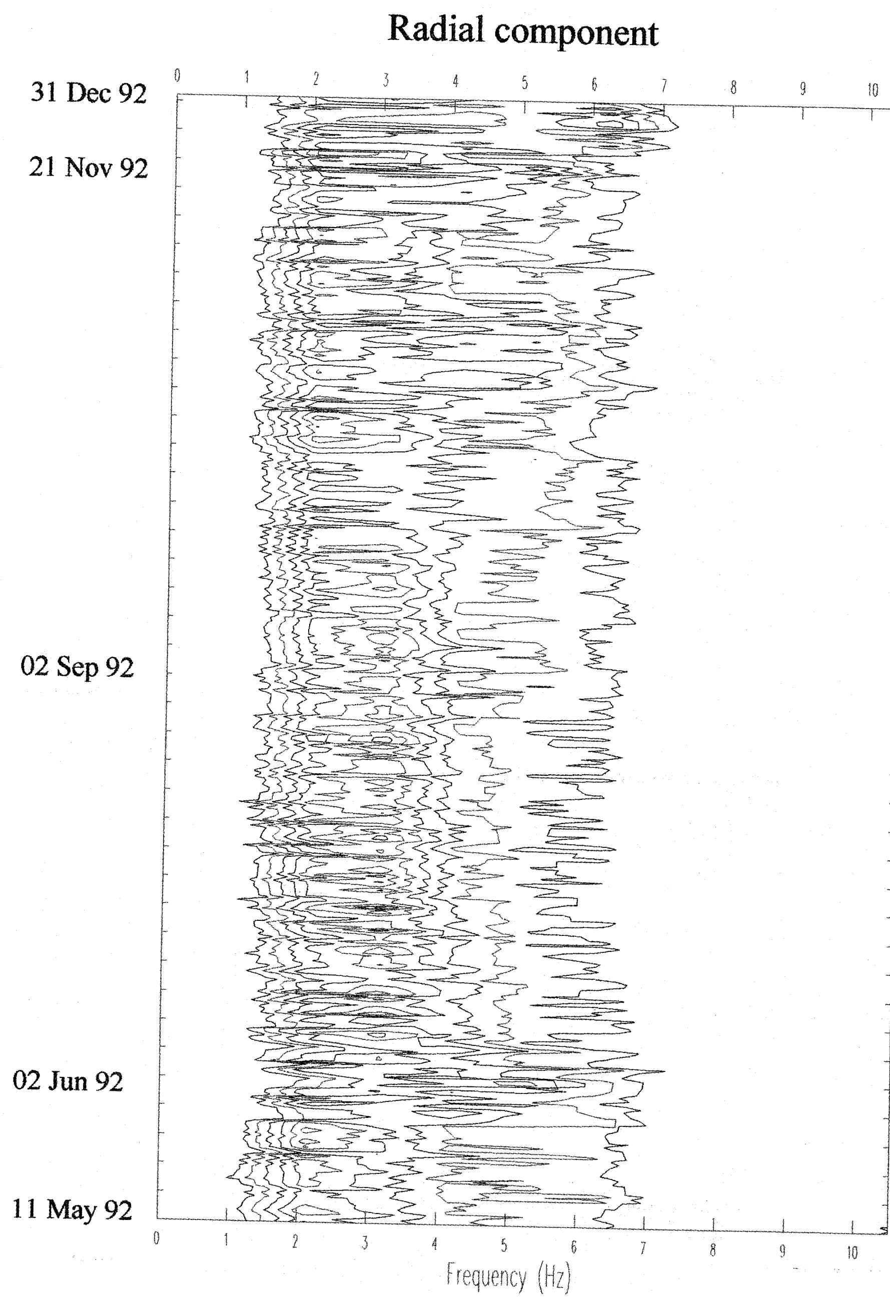


**Fig. 3.** Contour plot of hourly spectra of radial component during 1992. The data are mean values $S_j$ of 1 Hz wide sectors normalized by the mean value $S_{tot}$ computed over the whole range. 10 samples time averages were then taken in order to smooth the plot. Contour levels cover the $S_i/S_{tot}$ range 1.0.-2.4 with a uniform step of 0.2.

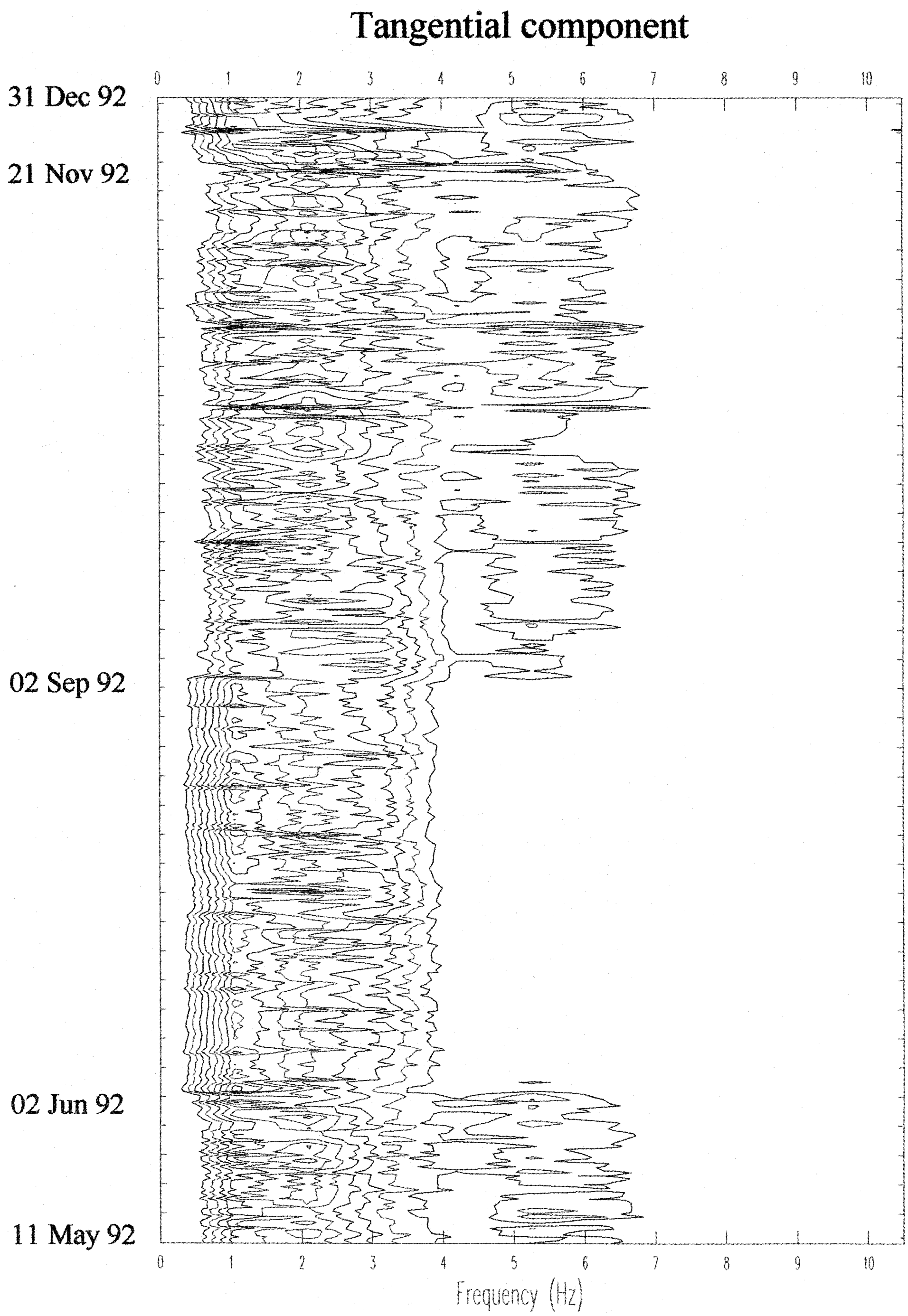


**Fig. 4.** Contour plot of hourly spectra of tangential component during 1992.

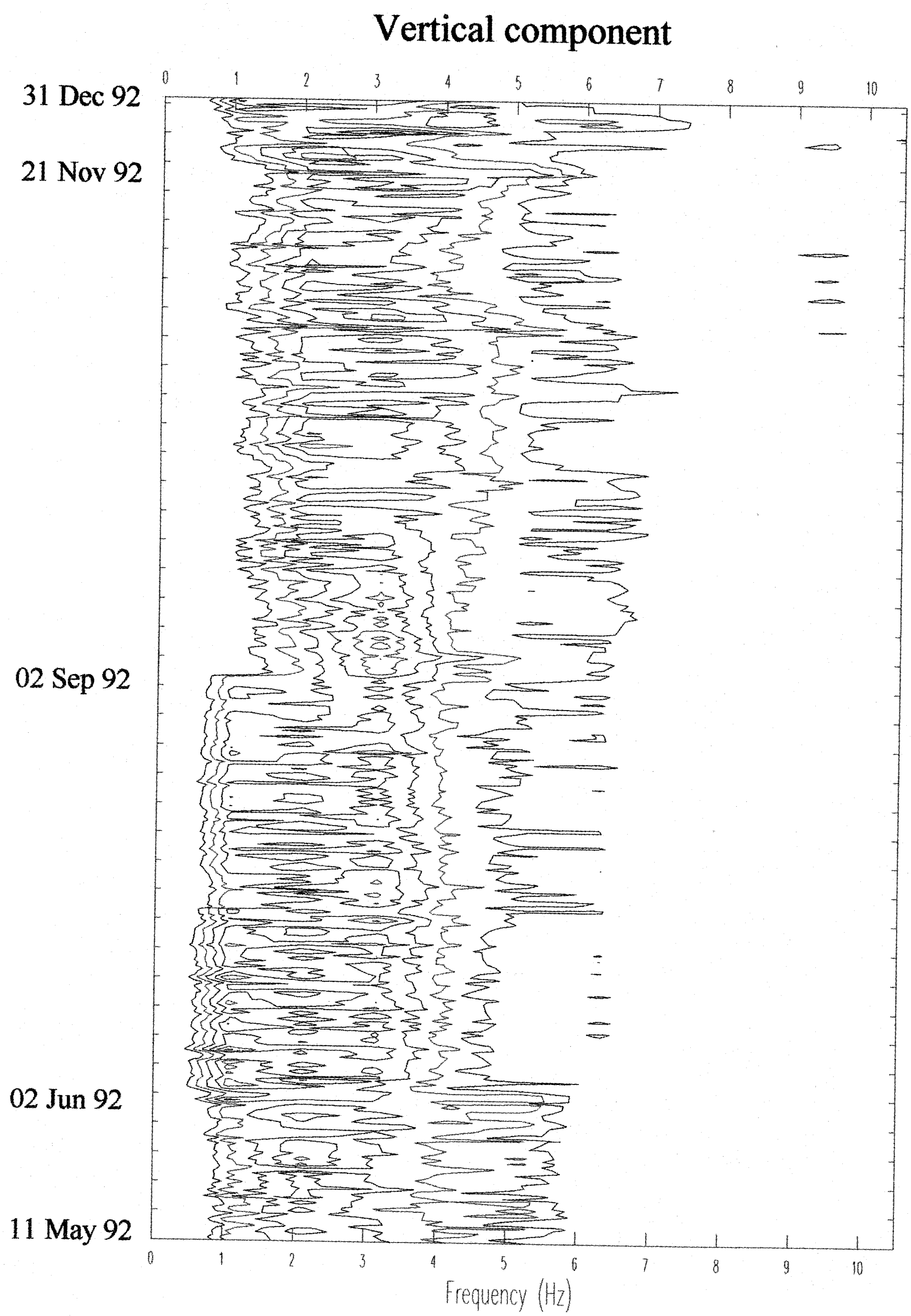


**Fig. 5.** Contour plot of hourly spectra of vertical component during 1992.

The end of the period of strong activity is again marked by a sharp change in the spectral content, observed on 21 November 1992. The radial component (see fig. 3) shows the disappearance of the 2 Hz peak, the other two components show a general small shift towards lower frequencies. The most important feature is the appearance of a peak near 1 Hz in the tangential component (see fig. 4) which will grow throughout December and January until the first paroxysmal phase of 1993. During this period of medium activity there is an isolated peak of tremor intensity on 6 December 1993.

The year 1993 is characterised by three strong volcanic crises and is therefore the most interesting in order to understand the seismic forerunners and consequences of a paroxysmal phase (Carniel *et al.*, 1994).

The beginning of the year is characterised by a spectrum showing most of the energy in the lower frequency range. The radial (see fig. 6) and the vertical (see fig. 8) components show most of their energy in the range around 3 Hz; in addition, the radial component shows another significant peak near 6 Hz, while the vertical shows an important contribution of the whole range between 1 and 3 Hz immediately before the crisis. This is confirmed by the direct analysis of the spectra (Carniel *et al.*, 1994), which highlights peaks centred around 1 and 1.25 Hz for the vertical and the tangential component, respectively. In particular, the peak in the vertical component at 1 Hz becomes more and more important with respect to the other peaks between 1 and 3 Hz, and therefore emerges in the normalised plot in the last period before the explosions. But the most interesting feature of the period preceding the paroxysmal phase is the build up of a single strong peak around 1 Hz in the tangential component. This peak is also well highlighted by the analysis of the behaviour of the relative normalised spectra (see fig. 7), where a very strong peak near 1 Hz can be noted, already described in the analysis of the spectral content at the end of 1992. It is worthwhile noting how the discretised and normalised analysis is able to underline slightly different features from the ones shown by the «normal» spectra. This suggests that the two kinds of analyses might offer complementary information in some cases.

A short series of violent explosions occurs on 10 February, 16.10 GMT, ejecting a large tephra column. Lithic blocks and lava fragments fall 1 km from the summit and heavy ashfall occurs at the village of Ginostra, about 2 km SW of the summit (GVN, 1993a). The seismic activity shows a very abrupt decrease after the explosions. This is also confirmed by records made at other seismic stations in the island (GVN, 1993a).

The concentration of energy in the frequency range below 3 Hz suddenly disappears immediately after the crisis, when the spectra become much more scattered over a large frequency range and show most of their energy in the range between 3 Hz and 8 Hz. The radial component in particular (see fig. 6) shows a clear peak near 5 Hz.

While the tremor amplitude is slowly increasing after the drop following the explosions of 10 February, the spectral content shows a noteworthy stability until 31 March 1993. Then, without any significant external manifestation, another abrupt spectral transition changes the distribution considerably: the 5 Hz peak in the radial component suddenly disappears (see fig. 6); a new peak appears in the vertical component around 4 Hz (see fig. 8); there is a general shift of the spectral content back towards lower frequencies, thus obtaining a distribution which is more similar to the one observed during the period before 10 February (see figs. 6, 7 and 8).

The seismicity, both in terms of tremor intensity and number of recorded events, continues to grow reaching a climax between 20 April and 26 May 1993 (see fig. 2). It is the second volcanic crisis of the year, characterised by very high Strombolian activity; the events recorded are very numerous and a good fraction of them saturate the acquisition system.

This activity culminates in a small lava flow which occurs on 16 May from the base of a cone in the NE crater. During the night the flow travels about 30 m down the slope, reaching the feeding fissure of the 1985 eruption

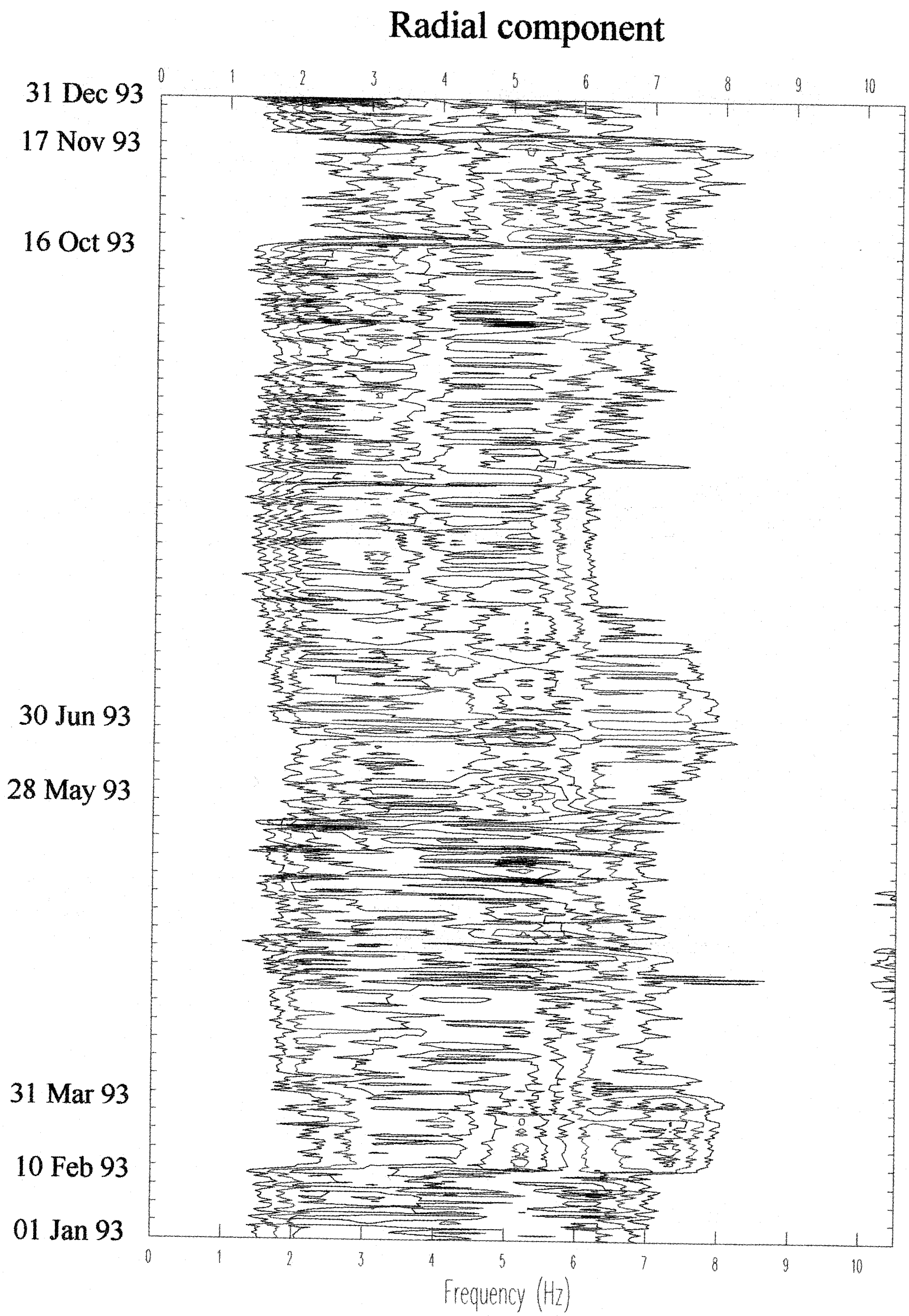


**Fig. 6.** Contour plot of hourly spectra of radial component during 1993.

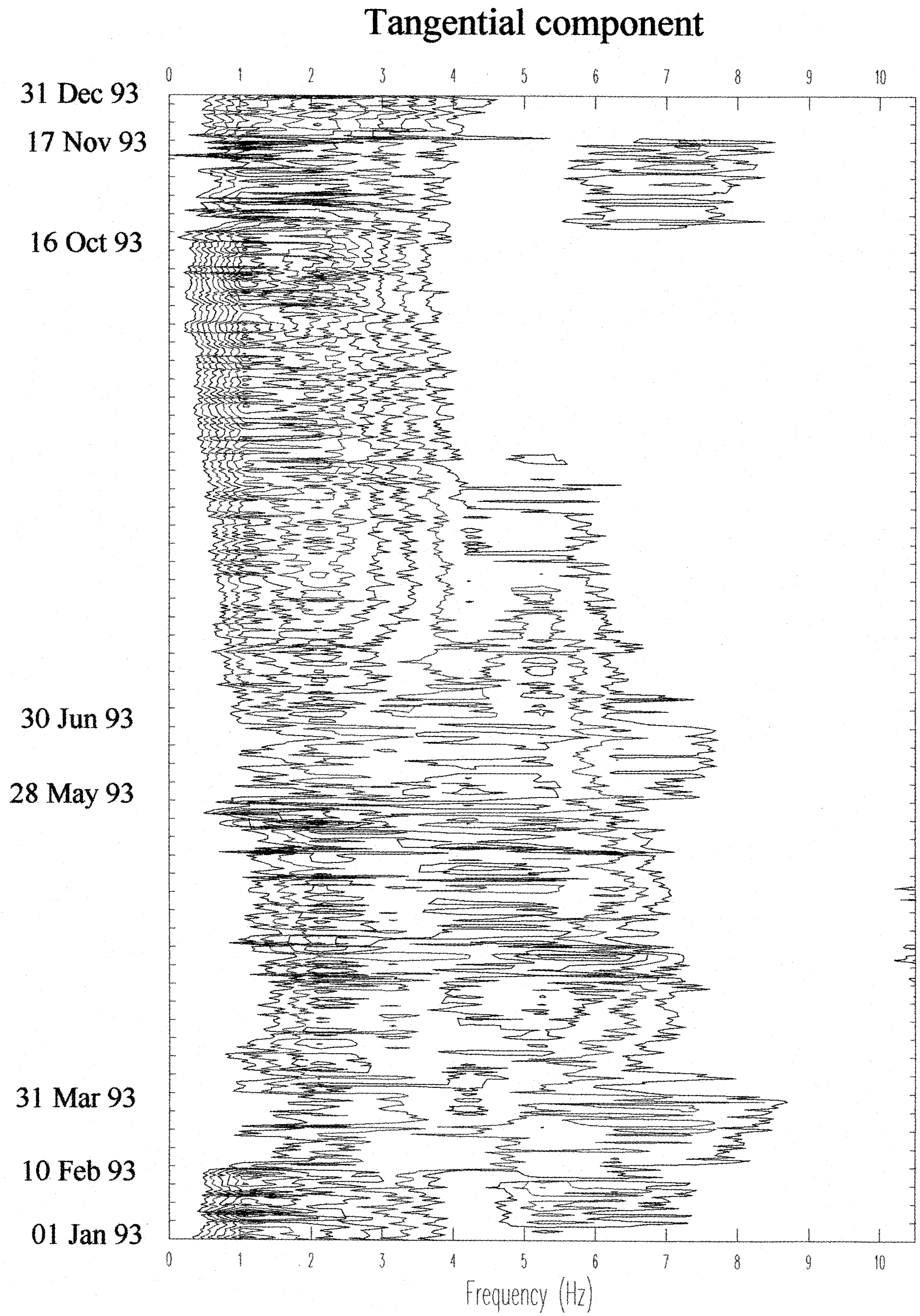


**Fig. 7.** Contour plot of hourly spectra of tangential component during 1993.

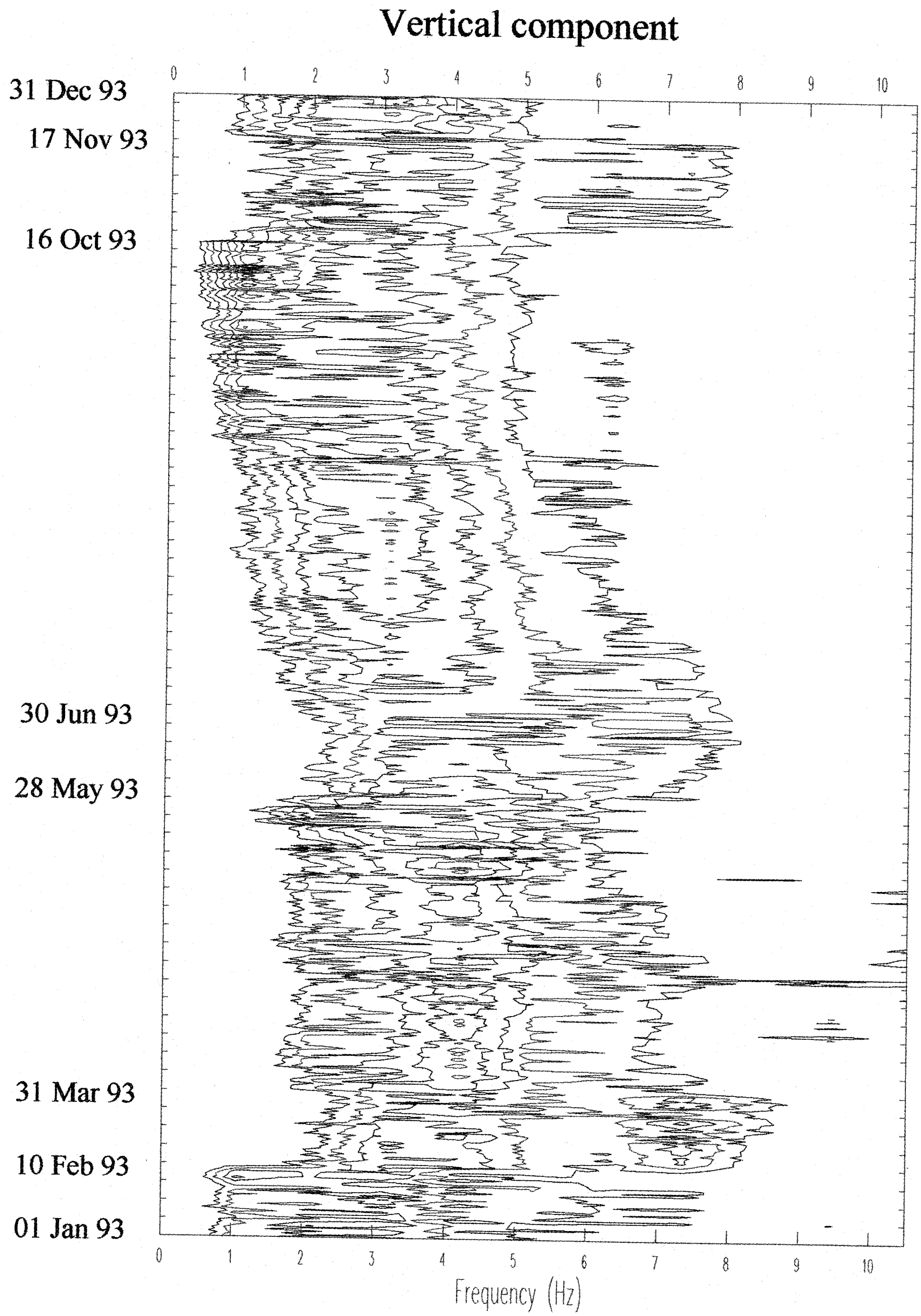


**Fig. 8.** Contour plot of hourly spectra of vertical component during 1993.

before stopping. The flow then resumes on 18 May, covering about 60 m of 1985 lava NE towards the very steep slope called «Sciara del Fuoco» (GVN, 1993b).

A slow decay of the tremor intensity, lasting five or six days, follows the end of the crisis; this is accompanied by a similar decay of the number of recorded shocks; the difference with respect to the end of the February crisis is mainly due to the rate of this decay (see fig. 2).

After the end of the period with strong Strombolian activity, in a couple of days (26-28 May 1993) the spectrum shows another rapid change. Once again the crisis is followed by a general shift towards higher frequencies. The new spectral distribution remains quite constant until 30 June, showing most of its energy in the range between 3 and 7 Hz, with a slight peak near 4 Hz in the tangential component (see fig. 7) and a more pronounced one around 5 Hz in the radial one (see fig. 6). Both these peaks tend to slowly disappear approaching the date of 30 June. Generally, there is a striking similarity to the period 10 February-31 March 1993, *i.e.* the one following the first crisis of the year, also for what concerns the trend of the number of events and of the tremor intensity: after the decay there is a slow increase in the seismicity in correspondence of the new stable spectral distribution.

Exactly as for the February crisis, another abrupt transition marks the end of the post-crisis spectral distribution. There is again an abrupt general shift towards lower frequencies, with most of the energy in the range from 2 to 6 Hz. The 5 Hz peak in the radial component disappears completely (see fig. 6) and a new phase begins, with a slow shift towards lower frequencies which continues and is more evident in the vertical component (see fig. 8).

As in January, significant peaks build up in the low frequency range: 3 Hz for the radial component (see fig. 6), between 1 and 2 Hz for the tangential (fig. 7) and vertical (fig. 8) component. Also the direct analysis of the spectra of the tangential and vertical components shows patterns very similar to the period preceding the 10 February explosions, *i.e.* significant peaks can be seen, centred at frequencies of 1.25 Hz and 1 Hz respectively (Carniel *et al.*, 1994).

On the contrary, no indication of a forthcoming crisis can be seen in the trend of the seismicity, which shows a slow decrease both in terms of tremor intensity and of number of explosion-quakes.

Two strong explosions felt at 1:10 GMT on 16 October destroy the small spatter cone that was built during the October 1990 eruption. Large blocks and spatter up to 2 m in diameter are ejected as far as 500 m from the crater, and reddish ash falls on the NW slope of the volcano along the «Sciara del Fuoco». One woman is injured by hot ashes near the crater area and some bushes catch fire along the slopes (GVN, 1993c).

Another abrupt change can be observed on 16 October: only one hour after the paroxysmal phase the spectrum shows already the new stable distribution which will last until 17 November. The higher frequencies again achieve a greater role: most of the energy is found now at frequencies between 3 and 7 Hz; the radial component in particular shows once again a striking similarity with spectra recorded in March and in June, with the very pronounced peak near 5 Hz (see fig. 6). This is confirmed to be a typical feature of the post-crisis stable spectral distribution. The usual abrupt decay of all features of the seismic activity, *i.e.* tremor intensity and number of recorded explosion-quakes, follows the explosions of 16 October; a slow increase in the seismicity follows.

Repeating a now well-known behaviour, on 16 November a sharp discontinuity in the spectral evolution marks the end of the post-crisis phase. The increase in the seismicity is now a bit steeper. A new configuration is reached, characterised by a predominance of the range from 2 to 5 Hz. There are significant peaks around 2 Hz in the tangential component (see fig. 7), around 3 Hz in the other two (figs. 6 and 8). This seems to be a pre-crisis distribution, but its duration is much longer than any other configuration observed; with very few changes, the tremor spectrum will maintain this appearance until the paroxysmal phase of summer 1994.

The first months of 1994 show little variation with respect to the configuration developed at the end of 1993. In particular, a noteworthy stability can be observed in the vertical and in the tangential component, where no evident changes show up until 5 June 1994. The tangential component (see fig. 10) shows most of the energy in the range between 1 and 4 Hz; the peak near 2 Hz, although slightly variable in amplitude is always present. The spectrum distribution of the vertical component (see fig. 11) shows a slow migration of its most important peak back and forth between the frequencies of 2 and 3 Hz.

The analysis of the spectrum of the radial component is the one that highlights small changes that allow the period between 17 November 1993 and 5 June 1994 to be divided into slightly different spectral configurations (see fig. 9). In fact on 13 January the spectrum shows an expansion of the most energetic range towards higher frequencies (up to 7 Hz); the 3 Hz peak is now less pronounced. On 9 March there is another abrupt transition that takes the distribution back to the previous situation, with a more concentrated spectrum (from 2 to 6 Hz) and a more consistent peak near 3 Hz.

In all the components a migration towards higher frequencies is observed on 27 March. This could be associated with the end of a period of more intense volcanic activity (from 10 March to 10 April) which is characterized by an increased number of saturated events. However, the real duration of this spectral phase is unfortunately not known; there is a lack of tremor data from 27 March to 18 May due to a problem with damaged magnetic tapes used for data storage.

During these months the activity in the crater area is characterized by the presence of a lava pond in a pit of the SW crater which displayed almost continuous spattering (GVN, 1994a).

Another transition can be seen on 5 June 1994. The change in the general distribution of the spectra is mostly given by a slight expansion of the energy content towards higher frequencies, up to 7 Hz. There is also the decrease in the low frequency peaks that dominated the preceding period, between 2 and 3 Hz in the different components.

The date of 5 June also marks the beginning of a period with an increasing number of saturated events in spite of a quite moderate seismicity as regards tremor intensity and total number of events.

When the number of saturating events decreases, the 2 Hz (vertical and tangential component) and 3 Hz (radial component) peaks again begin to grow, accompanying the increase in tremor intensity and total number of events during the second week of July.

On 12 July 1994 a slow transition begins, with increasing activity and a general shift towards higher frequencies (again up to 7 Hz). All three components show the disappearance of the 2-3 Hz peaks; although the spectra are quite spread, the higher weight can be ascribed to the 4-5 Hz range, with a very pronounced peak in the vertical component (see fig. 11). This is the spectral footprint of a period of very intense activity during July-August 1994, with significant morphologic changes in the crater area, *e.g.* the construction of three spatter cones in the NE crater (GVN, 1994b).

## 5. Conclusions

Starting from the very interesting preliminary results coming from the analysis of the periods near the three paroxysmal phases that characterised year 1993 on Stromboli (Carniel *et al.*, 1994), here we have investigated the features of the seismicity and the spectral content of the tremor in particular, during a much longer period of time. 1993 remains the year which offers the best highlights on the dynamics of the volcano but the comparison with the other years is essential in order to relate the analysis of paroxysmal phases to what is observed in periods of «normal» activity.

The first result of this work is that it confirms the observations which emerged from the previous analyses. In particular, it confirms the presence of abrupt transitions immediately after the paroxysmal phases, which mark

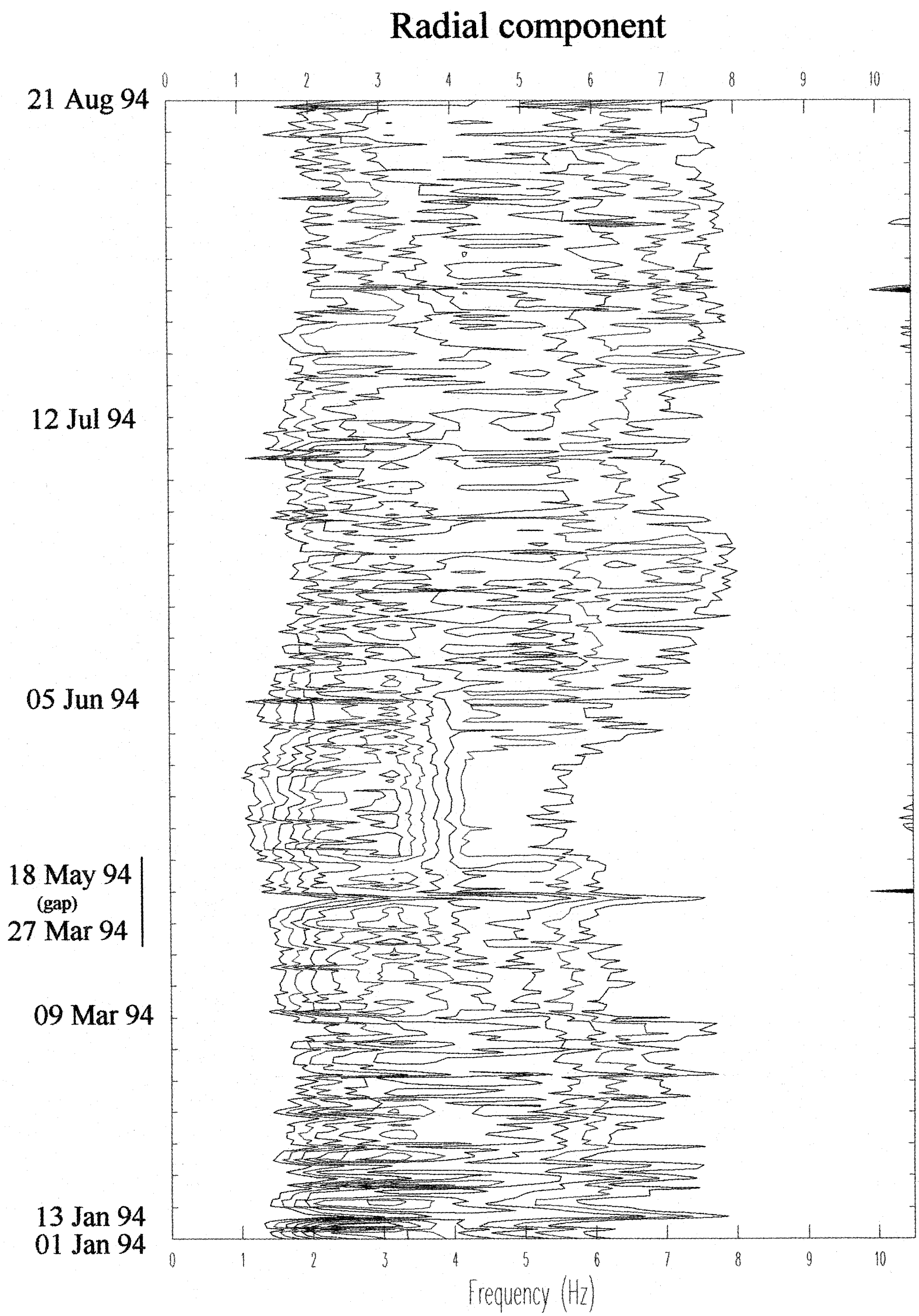


**Fig. 9.** Contour plot of hourly spectra of radial component during 1994.

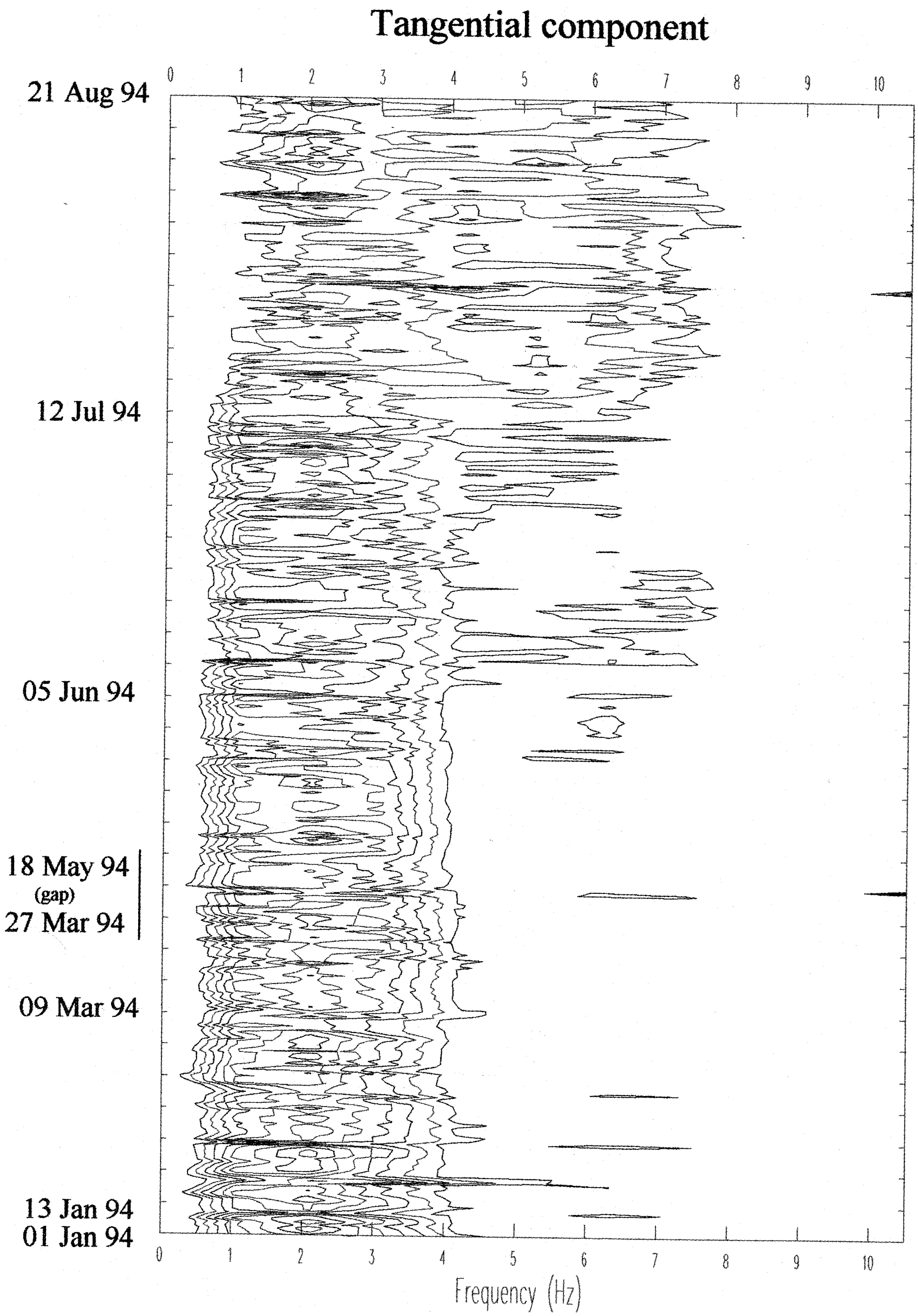


**Fig. 10.** Contour plot of hourly spectra of tangential component during 1994.

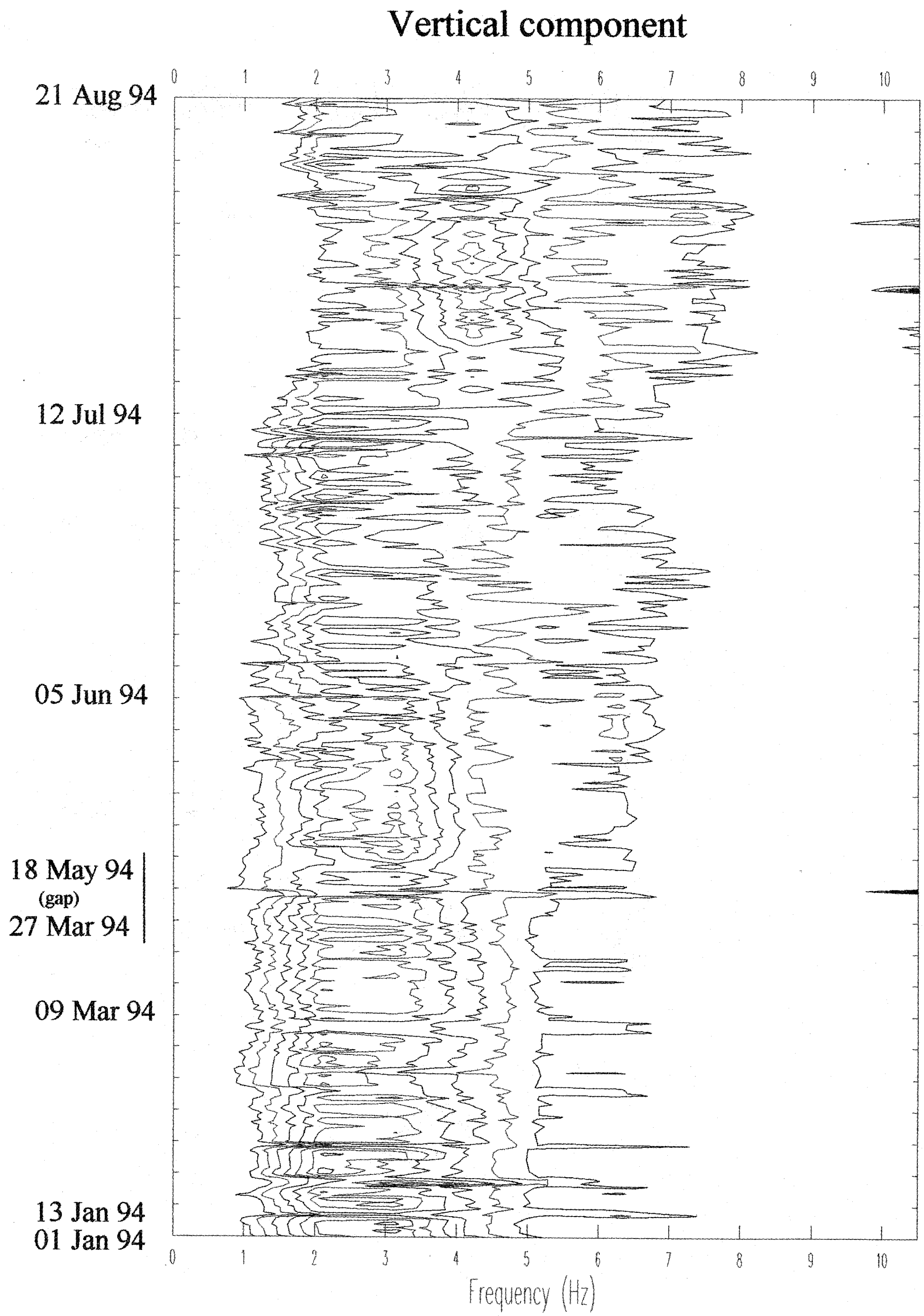


**Fig. 11.** Contour plot of hourly spectra of vertical component during 1994.

peculiar points in the time history of the dynamics of the volcano. The changes include spectral content, which shifts towards higher frequencies, and a quite fast decrease in seismicity as a whole, *i.e.* tremor intensity and total number of events. This decrease is then followed by a slow increase back to normal levels of seismicity.

This work inserts these observations into a more general framework. In fact, the abrupt spectral transitions seen immediately after a crisis are only examples of a common behaviour:

a) the tremor is shown to assume different spectral distribution which are mantained for weeks or even months without significant variations. This means that they represent «stable» states in terms of the configuration of networks of magma ducts feeding the vents, as well as of the geometry of the vents and/or of their (moderate) explosive activity;

b) the transitions between these «stable states» happen abruptly in most of the cases, although only for some of them the exciting cause may be associated to a strong visible explosive or effusive activity.

These results confirm the already well-known features of Stromboli in terms of stability and substantiate once more the choice of interpreting Stromboli as a dynamical system with mainly deterministic rules.

Although not useful in the search for precursors, one of the most interesting result of this analysis is the observation of the behaviour of the seismicity after the paroxysmal phases. In fact, after the abrupt change of the spectral content and intensity of the tremor and of the number of events, the slow increase in the seismicity that takes the system back to «normal» level is accompanied by a spectral distribution that shows a noteworthy stability for a period of one month or more. Moreover, the spectral distributions observed after the paroxysmal phases of 1993 show an impressive similarity; in particular, a peak near 5 Hz in the radial component is an evident common feature of these three post-crisis periods.

When the level of seismicity reaches a value which may be considered «normal» the spectral distribution described suddenly disappears through an abrupt transition that does not show any evident correlation with the external activity. It seems, therefore, that this spectral configuration is typical for a post-crisis stable state that is associated to a sort of «recharging» phase of the volcano; however one has to keep in mind that Stromboli is an open conduit volcano.

While it is reasonable to assume major changes in the geometry of the volcanic ducts during the large explosions, and to associate the change in the tremor spectral content (and in the eruptive activity) to a decrease in the magma level, it is very difficult to explain the abrupt spectral transition at the end of the post-crisis state. This may be related to the return of the magma to a particular section of the ducts where the «normal» tremor is generated. The abruptness of the transition may be due to some geometric discontinuity in the ducts or could be ascribed to some kind of external (deterministic or random) triggering, such as tides or atmospheric pressure changes. We have to remember that in a nonlinear and possibly chaotic system minor changes may also trigger strong effects. Although these are just speculations, in our opinion the discovery of this abrupt transition is extremely important and every new model of the volcano will have to deal with this new «boundary condition».

However, the most important periods to analyse are the ones preceding the paroxysmal phases, *i.e.* the ones in which a search for forerunners can be carried out. Although most of previous works had suggested investigating the time and amplitude distribution of the explosion-quakes (Schick and Müller, 1985) (Falsaperla and Neri, 1986), no marked modification of seismicity preceded the 1985 eruption, when only slight variations were observed in microearthquakes amplitude distribution (Falsaperla and Neri, 1986), and no common features could be highlighted in this study for the periods preceding the three crises in 1993, in which the seismicity was in turn stable, increasing and decreasing.

Some interesting results were found looking at tremor before the June-October 1990 crisis (Riuscetti, 1994), where the transition from a spectrum distribution characterised by a marked multimodality to one dominated by a sharp spectral line below 4 Hz was observed. This, together with the observation that no precursors of any kind can be found in the composition of the tremor before a «normal» Strombolian eruption (Schick and Müller, 1985) suggests that only «stronger» explosions have such a spectral precursor.

In the preliminary analysis of the three crises of 1993 (Carniel *et al.*, 1994), a trend towards the concentration of tremor energy in the low-frequency range (below 5 Hz) was again observed; the building up of clear peaks could be recognised especially before the explosions in February and October.

This observation is fully confirmed by this long term analysis. Peaks can often be observed very clearly also in the rougher discretised representation presented here, and the ones leading to a crisis seem to be always located in the lowest range of the spectrum, *i.e.* below 3 Hz. Unfortunately, the concentration of energy in this frequency range can be observed also for very long periods of time, *e.g.*. the one leading to the weeks of strong Strombolian activity during July and August 1994, so that no simple criterion can be defined in order to forecast the time of occurrence of a paroxysmal phase. However, the spectral analysis of the tremor is confirmed to be essential for understanding «what's going on» inside Stromboli.

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